

# FUSE Deuterium Observations: A Strong Case For Galactic Infall

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## Abstract.

Measurements of deuterium in the local interstellar medium have revealed large variations in D/H along different lines of sight. Moreover, recent *Far Ultraviolet Spectroscopic Explorer* (FUSE) measurements find D/H to be anticorrelated with several indicators of dust formation and survival, suggesting that interstellar deuterium suffers significant depletion onto dust grains. This in turn implies that the total deuterium abundance in the local Galactic disk could be as high as  $\sim 84\%$  of the primordial D abundance. Because deuterium is destroyed in stars, its abundance in the interstellar medium (ISM) also tells us about the fraction of material which has never been processed through stellar environments. Therefore, the new report of such high ISM deuterium abundance implies that *most* present-day interstellar baryons are *unprocessed*. It was proposed that the infall/accretion of pristine gas is needed to explain such a high deuterium abundance. However, we point out that the infall needed to maintain a high present-day D/H is, within the preferred models, in tension with observations that gas represents only some  $\sim 20\%$  of Galactic baryons, with the balance in stars. This small gas fraction implies that, integrated over Galactic history, *most* baryons have been sequestered into stars and stellar remnants. We study this tension in the context of a wide class of Galactic evolution models for baryonic processing through stars, which show that deuterium destruction is strongly and cleanly correlated with the drop in the gas fraction. We find that FUSE deuterium observations and Galactic gas fraction estimates can be reconciled in some models; these demand a significant infall rate of pristine material that almost completely balances the rate of star formation. These successful models also require that the average fraction of gas that is returned by dying stars is less than 40% of the initial stellar mass. Cosmological implications of dust depletion of D in high-redshift systems are discussed.

## 1. Introduction

Deuterium has a unique nucleosynthetic property that it is only created in the big bang nucleosynthesis (BBN) while all other processes, due to deuterium’s fragile nature, destroy it [1, 2]. Thus the deuterium abundance should monotonically decrease after BBN. This gives deuterium a key role in cosmology as a cosmic “baryometer” [3]. Unlike any other light element, deuterium provides a precise measure of the primordial abundance but it can also serve as a probe of how much gas was processed in stars.

High-redshift ( $z \sim 3$ ) D observations in QSO absorption systems give a deuterium abundance  $(D/H)_{\text{QSOALS}} = (2.82 \pm 0.27) \times 10^{-5}$  [4], which is in agreement with the one inferred [5, 6, 7] from big-bang nucleosynthesis calculations in concert with the WMAP determination of the baryon-to-photon ratio. This concordance of BBN theory at  $z \sim 10^{10}$ , CMB theory and observation at  $z \sim 1000$ , and QSO observations at  $z \sim 3$  is a strong test of the hot big bang and marks a major achievement of the standard cosmology.

However, measurements of the deuterium abundance in the local interstellar medium (ISM) have within a past decade revealed large variations over different lines of sight (see eg. [8, 9, 10]). Recent FUSE observations [11, 12] showed that these variations can be greater than a factor of 3. In the hot Local Bubble immediately surrounding the Sun, FUSE observations have very precisely measured a deuterium abundance  $(D/H)_{\text{ISM}} = (1.56 \pm 0.04) \times 10^{-5}$  [13]. Over more distant lines of sight FUSE finds large variations in gas-phase deuterium, with values scattering far above and below the Local Bubble measurement; [12] tabulate values spanning  $(D/H)_{\text{ISM}} = (0.5 - 2.2) \times 10^{-5}$ .

Linsky *et al.* [12] have argued that deuterium is depleted onto dust grains efficiently [16, 15], and preferentially relative to hydrogen. In support of this hypothesis, they show that  $D/H$  is significantly anticorrelated with the depletion of refractory elements like iron and silicon, and positively correlated with  $H_2$  rotational temperature. These trends imply that D itself is highly refractory, and that its gas-phase abundance is highest in environments likely to erode or destroy dust grains. These trends are also the opposite of naive expectations that local nucleosynthetic enrichment of metals by stellar ejecta should be anticorrelated with deuterium which has been astrated.

If significant amounts of deuterium are indeed locked in dust grains, then the gas-phase D abundance is only a lower limit to the total interstellar D inventory. Linsky *et al.* [12] argue that the *true* interstellar deuterium abundance lies at the upper end of the distribution of gas-phase measurements, and estimate  $(D/H)_{\text{ISM+dust}} \geq (2.31 \pm 0.24) \times 10^{-5}$ . This value is consistent with the recent deuterium measurement in the warm gas of lower Galactic halo where  $D/H = 2.2^{+0.8}_{-0.6} \times 10^{-5}$  [17]. If the interstellar deuterium abundance is indeed as large as these recent data suggest, it remains surprisingly close to the primordial deuterium abundance.

The ratio  $(D/H)_{\text{ISM}}/(D/H)_p$  of the *total* (including the potential dust-depleted fraction) deuterium abundance in the *present* interstellar medium to the primordial value has long been recognized as a key probe of Galactic evolution. Specifically, this

ratio quantifies the fraction of material in the present-day ISM which has *never* been processed through stars. For the purpose of our work we will adopt the primordial deuterium abundance of  $(D/H)_p = 2.75^{+0.24}_{-0.19} \times 10^{-5}$  [5]. This value is consistent, within errors, with other calculations [6, 7, 14] but is the highest central value of WMAP-based evaluations and thus gives the most conservative ISM-to-primordial deuterium abundance ratio. For the ISM deuterium abundance we will use a range of gas-phase deuterium  $(D/H)_{ISM} = (0.5 - 2.2) \times 10^{-5}$  [12] with the central value of  $(D/H)_{ISM} = (1.56 \pm 0.04) \times 10^{-5}$  [13]. With this choice of abundances we find that the interstellar gas-phase deuterium is a fraction

$$\frac{(D/H)_{ISM}}{(D/H)_p} = 0.57^{+0.23}_{-0.52} \quad (1)$$

of the primordial value. Note that large errors quoted in 1 originate mainly from using the entire observed ISM deuterium abundance range. However, Linsky *et al.* [12] FUSE ISM deuterium analysis corrects this fraction upwards to account for dust depletion, giving

$$\frac{(D/H)_{ISM+dust}}{(D/H)_p} = 0.84 \pm 0.09 \quad (2)$$

which is significantly higher. Taken at face value, this new value suggests that the *majority* of baryons in the present Galactic ISM have never been processed through stars!

This new provocative result has important consequences for the nature of the interstellar medium as well as for D evolution, and all of its implications have only begun to be tested. Such tests appeared in [18, 19], but with mixed results. Noting the highly refractory nature of titanium, [18, 19] examine the observed correlation between local Ti/H and D/H abundances. While a tight correlation is found, its comparison with correlations of other refractory elements does not yield a consistent picture. Specifically, Fe and Si, which are less refractory than Ti, show steeper correlation with D/H, contrary to what is expected [19]. These results [19] have been reinforced by another recent study [20]. On the other hand, if depletion onto dust was the cause of low deuterium abundances at some lines of sight, one would also expect anticorrelation between D/H and reddening effects along the same line of sight. This test was done in [21], and again contrary to the expectations, they found multiple cases where low D abundances were observed along some of the lines of sight that showed the lowest reddening.

For the purpose of this paper we adopt the Linsky *et al.* [12] interpretation that the large scatter in the local deuterium measurements is truly due to large depletion of deuterium onto dust, and thus examine the consequences of the resulting true local deuterium abundance that is now close to its primordial value.

Though some Galactic chemical evolution (GCE) models can be consistent with high observed D abundances and the high value of the true abundance [12], most of them require some continuous infall of primordial gas that would replenish the ISM deuterium [22]. Moreover, the infall of deuterium-rich material also seems to be needed in order

to explain high deuterium abundances that were observed in the Galactic Center [23]. Turning to cosmological scales, both infall (accretion) and outflows appear in models of cosmic chemical evolution [24, 25] and in the cosmic context, deuterium astration has been shown to be sensitive to the details of gas processing into stars and flows in and out of galaxies [26]. Thus, we reexamine the infall rates needed to explain such high local deuterium abundance, and moreover, analyze the consequences that such result bears for high-redshift deuterium observations.

In particular, we find that combining the new local deuterium observations of Linsky *et al.* [12] with even a wide uncertainty range of measurements of the gas mass fraction [27, 28, 29], can be, within a simple GCE model [31] and with some adopted stellar processing return fraction (fraction of stellar mass that is returned to the ISM in the instantaneous recycling approximation), very constraining for the required and allowed infall rates. The tightness of such constraint then only depends on the assumed return fraction. Specifically, adopting a higher return fraction value narrows down the infall rate constraint to almost a single value—star-formation is almost completely balanced by the infall. On the other hand, a lower return fraction leaves room for some wider, but still quite constraining, range of infall rates, where non-zero infall is required. Thus, the combination of the two observables, local deuterium abundance measurements of FUSE and the gas mass fraction, becomes a very powerful and constraining probe of the infall rates.

Finally, in the Appendix A of this paper we also point out a “universality” in deuterium evolution within GCE infall models, where we find that infall GCE models for deuterium evolution *versus metal yields* show convergent behavior nearly independent of the rates of primordial gas infall.

Though the new high estimate of the true local deuterium abundance does intuitively indicate large infall at play, only in concert with gas mass fraction estimates does it become a strong constraint of the infall rate, while it on the other hand does not necessarily require large metal yields.

## 2. Infall and Chemical Evolution of the Milky Way

### 2.1. Formalism

We construct a model for Galactic evolution with infall. To characterize the infall rate, we adopt such parameterization [33] in which the gas mass infall rate (i.e., baryonic accretion rate) is arbitrarily proportional to the star formation rate

$$\frac{dM_{\text{baryon}}}{dt} = \alpha\psi \quad (3)$$

Here  $\psi(t)$  is the star formation rate, while  $\alpha$  is the proportionality constant which characterizes the strength of infall [33].

The infall prescription of (3) offers (for constant  $\alpha$ ) great mathematical convenience, but must be justified on physical grounds. Models of this sort have been used to study

chemical evolution of the cosmic ensemble of galaxies [24]. Remarkably, the underlying infall/star-formation connection in these simple heuristic models find support in the detailed *ab initio* simulations [34] that follow forming galaxies in a  $\Lambda$ CDM universe with gas dynamics and subgrid prescriptions for star formation and feedback. These models [34] find that from  $z = 0-5$ , the global-averaged cosmic star formation rate and galactic gas accretion rates not only are nearly proportional, but moreover the rates are nearly identical, i.e., in our language their results give a nearly constant value  $\alpha \approx 1$  over this large range in redshift and time. Observationally, a strong correlation between gas fraction and present-to-integrated star formation rate, as measured by the  $u-K$  color, has been found [35]. This suggests that gas availability rapidly leads to, and possibly regulates, gas consumption via star formation; this is also what is implied by (3).

In this estimate we will assume that the infalling material is pristine and that the deuterium abundance in the infalling gas is primordial. This assumption is supported by observations of low-metallicity high-velocity clouds where deuterium abundance was measured to be close to primordial [36]. Moreover, due to the fragile nature of deuterium we can safely assume that all of the deuterium is destroyed once it gets in stars. Thus, following [31, 32], we have

$$\frac{dM_{\text{ISM}}}{dt} = -(1-R)\psi + \alpha\psi \quad (4)$$

$$\frac{d}{dt}(DM_{\text{ISM}}) = -D\psi + D_p\alpha\psi \quad (5)$$

Here  $M_{\text{ISM}}$  is the ISM mass (gas+dust) while  $R$  is the return fraction, i.e., the fraction of stellar mass that is returned to the ISM in the instantaneous recycling approximation.  $D$  is the deuterium mass fraction for a given epoch  $X_D \equiv \rho_D/\rho_{\text{baryon}}$ , which we can write as

$$D \equiv X_D \cong 2 \left( \frac{D}{H} \right) X_H \quad (6)$$

where  $X_H$  is the hydrogen mass fraction. Primordial deuterium mass fraction is labeled as  $D_p$ .

Gas accretion through infall and processing through stars both change the ISM gas mass. It is convenient to quantify these effects via the ratio  $\mu \equiv M_{\text{ISM}}(t)/M_{\text{baryon},0}$  of gas at time  $t$  to the initial baryonic mass  $M_{\text{baryon},0}$ . This quantifies the significance of infall, because when  $\alpha + R > 1$  infall dominates the gas content of the Galaxy and  $\mu$  increases with time; otherwise,  $\mu$  decreases with time, the same qualitative trend as in the closed-box model i.e., the zero-infall limit, in which case  $\mu \rightarrow \omega$  as in (10). Note also that the ratio of *total* baryonic mass to initial mass is

$$\mu_{\text{tot}} \equiv M_{\text{baryon}}(t)/M_{\text{baryon},0} = 1 + \alpha \frac{\mu - 1}{\alpha + R - 1} \quad (7)$$

The total integrated accreted mass is thus measured by  $\mu_{\text{tot}}$ , and one can verify that this expression has  $\mu_{\text{tot}} > 1$  for all  $\alpha > 0$ .

Combining (4) and (5) we find the rate of change of deuterium mass fraction  $D$  as

$$M_{\text{ISM}} \frac{dD}{dM_{\text{ISM}}} = \frac{-RD + \alpha(D_p - D)}{\alpha + R - 1} \quad (8)$$

Integrating the above equation in the limits where D mass fraction goes from primordial  $D_p$  to present day value  $D(t)$ , we find the solution for deuterium fraction evolution

$$\frac{D(t)}{D_p} = \frac{R}{\alpha + R} \left( \frac{\alpha}{R} + \mu^{\frac{\alpha+R}{1-\alpha-R}} \right) \quad (9)$$

We see that the dimensionless deuterium mass fraction ratio depends only on the dimensionless gas mass ratio  $\mu$  and thus is insensitive to the absolute Galactic gas mass.

Another observable which directly encodes Galactic baryonic processing both in star formation and in infall is the present gas mass fraction  $\omega \equiv M_{\text{ISM}}(t)/M_{\text{baryon}}(t)$ . Combining (3) and (4) we find

$$\omega(t) \equiv \frac{M_{\text{ISM}}}{M_{\text{baryon}}} = \frac{1 - R - \alpha}{1 - R - \alpha\mu(t)} \mu(t). \quad (10)$$

Equations (9) and (10) relate observables to the model parameters; given a choice of return fraction  $R$  (i.e., a choice of the initial mass function), these two equations set values for the unknowns  $\alpha$  and  $\mu$  (and/or  $\mu_{\text{tot}}$ ), which together respectively quantify the current and integrated rates of Galactic infall.

The deuterium mass fraction and gas fraction are both excellent probes of Galactic evolution – as these observables trace stellar processing in a particularly clean way. In our model, both  $D/D_p$  and  $\omega$  decrease monotonically with time. Their declines are correlated due to the physics which drives their evolution: stellar processing both destroys deuterium and locks up baryons into low-mass stars and remnants. We can exploit this correlation to gain insight into Galactic evolution in general and infall in particular.

At late times, both the deuterium fraction and the gas fraction approach *minimum* values, regardless of the detailed star formation history. At late times and for large infall ( $\alpha + R > 1$ ) the parameter  $\mu^{\frac{\alpha+R}{1-\alpha-R}} \rightarrow 0$ , but this also stays true for small infall ( $\alpha + R < 1$ ) scenario since  $\mu \rightarrow 0$ . Therefore, we see that in both cases, the ratio of deuterium fractions from (9) goes to a minimum value

$$\frac{D}{D_p} \rightarrow \frac{D_{\text{min}}}{D_p} = \frac{\alpha}{\alpha + R} \quad (11)$$

which is the ratio of D-inflow to gas-mass-injection rates. In this same late-time limit, if infall is large enough so that  $\alpha > 1 - R$ , the gas mass fraction will go to a constant which we find in the large- $\mu$  limit of (10):

$$\omega \rightarrow \omega_{\text{min}} = 1 - \frac{1 - R}{\alpha} \quad (12)$$

i.e., the gas fraction is just given by the ratio of the rates of gas (4) to total (3) mass increase. On the other hand, if the infall is small enough that  $\alpha < 1 - R$ , we will have  $\mu \rightarrow 0$  and thus  $\omega_{\text{min}} \rightarrow 0$ ; there is no lower limit to the gas fraction.

Thus measurements of deuterium and the ISM gas content each place *upper* bounds on infall. Namely, requiring  $D_{\text{min}} < D_{\text{obs}}$  forces

$$\alpha < \frac{D_{\text{obs}}/D_p}{1 - D_{\text{obs}}/D_p} R \quad (13)$$

Similarly, demanding  $\omega_{\min} > \omega_{\text{obs}}$  requires

$$\alpha < \frac{1 - R}{1 - \omega_{\text{obs}}} \quad (14)$$

We emphasize that these limits are independent of the details of star formation history, and free of any uncertainties in nucleosynthesis yields since metallicity does not enter at all (and deuterium is totally destroyed in stars).

The minima in (11) and (12) teach important lessons for Galactic evolution. In models without infall, both deuterium and interstellar gas approach zero as stellar processing becomes large. Hence a closed box can only accommodate the high FUSE deuterium if there is little processing, and thus necessarily a high gas fraction. As we will see, this arrangement is ruled out in realistic models. But we see that the presence of infall—i.e., nonzero  $\alpha$ —places nonzero *lower* bounds on deuterium and gas fractions. Physically, this is of course because primordial infall replenishes interstellar gas and deuterium. The presence of infall thus opens the possibility that the high deuterium abundances seen by FUSE can be reconciled with significant stellar processing. But this possibility does not guarantee a solution, as nonzero infall also raises the gas fraction, which may or may not remain in agreement with observations.

Thus we see that once a return fraction  $R$  has been specified, one can constrain infall based on deuterium and/or gas observations. As we will see, using present observations, these limits are quite constraining. Also, the two limits are independent, and for present observations are competitive with each other.

## 2.2. Model Input Parameters and Observational Constraints

Our goal is to use deuterium and gas fraction observations in the context of our model to probe Galactic infall. To do this, we must specify the observed constraints and their uncertainties. In the model, infall is parameterized via its ratio  $\alpha$  to the star formation rate; in addition, we must also specify the return fraction  $R$  which too has uncertainties which we must address.

The chemical evolution formalism most naturally uses mass fraction as an abundance measure. For this reason, relate the D/H ratio to the mass fraction  $D$  via the definition (6) as

$$\frac{D_{\text{ISM}}}{D_{\text{p}}} = \frac{X_{D,\text{ISM}}}{X_{D,\text{p}}} = \frac{X_{H,\text{ISM}}}{X_{H,\text{p}}} \frac{(D/H)_{\text{ISM}}}{(D/H)_{\text{p}}} \quad (15)$$

Following this we convert the D/H observational constraints in (1) and (2) to reflect corresponding mass fractions

$$\frac{D_{\text{ISM}}}{D_{\text{p}}} = 0.53^{+0.22}_{-0.36} \quad (16)$$

$$\frac{D_{\text{ISM+dust}}}{D_{\text{p}}} = 0.78^{+0.11}_{-0.10} \quad (17)$$

where we have used the ratio of hydrogen ISM-to-primordial mass fraction  $X_{H,\text{ISM}}/X_{H,\text{p}} = 0.93$  [37, 6].

The present Galactic interstellar gas mass is known to within a factor  $\sim 2$  [27, 28, 29]

$$\omega_{\text{obs}} \equiv \left( \frac{M_{\text{ISM,MW}}}{M_{\text{baryon,MW}}} \right)_{\text{obs}} \sim 0.07 - 0.30 \quad (18)$$

which is typical for similar type spiral galaxies (see eg. [30]). We will see that even with these significant uncertainties, we can place strong constraints on the infall rate  $\alpha$ .

To estimate the return fraction  $R$ , i.e. the mass fraction of stellar population that is returned to the ISM, we use the approximation of [38] to determine stellar remnant masses  $m_{\text{rem}}(m)$  and thus to determine the returned mass  $m_{\text{ej}}(m) = m - m_{\text{rem}}(m)$ . If one defines a return fraction  $R(m) = m_{\text{ej}}(m)/m$  for each progenitor mass  $m$ , then the global return fraction thus represents a mass-weighted average of this quantity over the initial mass function (IMF)  $\phi(m) \equiv dN/dm$ :

$$R = \frac{\int_{m_L}^{m_U} dm R(m) m \phi(m)}{\int_{m_L}^{m_U} dm m \phi(m)} \quad (19)$$

For our numerical results we adopt mass ranges  $8 \leq m_{\text{SN}}/M_{\odot} \leq 100$  and  $0.8 \leq m_{\text{AGB}}/M_{\odot} \leq 8$ . Using these with the IMF in the form of [39]  $\phi(m) \propto m^{-2.35}$ , we find  $R = 0.31$ , which, to the first decimal, does not change with changing mass ranges of a given stellar population. Of course, the return fraction strongly depends on the choice of the IMF. Though widely used and informative, this IMF [39] is not a realistic one. Adopting a modern and more realistic IMF [40, 41] that is flatter in the higher-mass regime would obviously yield a larger return fraction closer to  $R \sim 0.4$ . On the other hand, it is still possible to engineer smaller return fractions. For example, some very massive stars may collapse directly to a black hole without first returning their nucleosynthetic products [42]. This would introduce a cutoff in mass above which there would be no gas return, which would in turn result in a lower return fraction.

We will find that for only some values of  $R$  is it even *possible* to find a Galactic evolution model which fits both high present-day interstellar deuterium and the observed gas fraction. Thus these observations could provide hints about the IMF, its mass limits, and the physics of stellar gas return. To illustrate the possibilities, we will present our results for the case of  $R = 0.3$  but also for a range of  $R \in (0.1, 0.5)$ . As we will see, when solutions are possible, uncertainties in  $R$  allow a wider infall rate range.

### 2.3. Model Results

Presented on Figure 1 is the ISM-to-primordial deuterium ratio as a function of the present gas mass fraction for two different return fractions. Different curves on the same panel reflect different infall rates. The two bands in the  $D_{\text{ISM}}/D_p$  reflect the ratio of FUSE measured  $D_{\text{ISM}}$  with and without accounting for the possible dust depletion to the primordial value. These correspond to top (cyan) band, which includes corrections for a severe dust depletion and the central value of (17) [12], and bottom (yellow) band with the central value given by gas-phase abundances only (16). The width of the lower band was dictated by the scatter of deuterium ISM measurements where the limits came



from the highest and the lowest observed deuterium abundances in the ISM [12]. The adopted primordial deuterium abundance is that of Cyburt *et al.* [5]. The vertical (yellow) band in the present gas mass fraction reflects the observed range of values for  $\omega_{\text{obs}}$  in (18) depending on the adopted model (within errors).

Figure 1 shows that when the gas fraction is large, the rate of infall is not important and thus all curves that reflect different infall rate  $\alpha$  converge. However, in the low gas mass fraction range which is the one consistent with observations, we see that different infall rate curves behave very differently. Thus we see that the overlap region between the observed  $\omega$  and the ratio of the new deuterium FUSE measurement that corrects for the dust depletion (top band) to the primordial value, can be quite constraining of the infall rate. Specifically, from the left panel ( $R = 0.2$ ) we see that all infall rates that are lower than the star formation rate, i.e.  $\alpha \lesssim 1.0$ , can be consistent with the measured mass fraction range. On the other hand, adopting a higher return fraction of  $R = 0.3$ , as presented on the right panel, is more constraining, and it allows for only  $0.5 \lesssim \alpha \lesssim 1.0$ . We note that the infall rate that is comparable to the star-formation rate is consistent with the cosmic-averaged accretion rate found in [34].

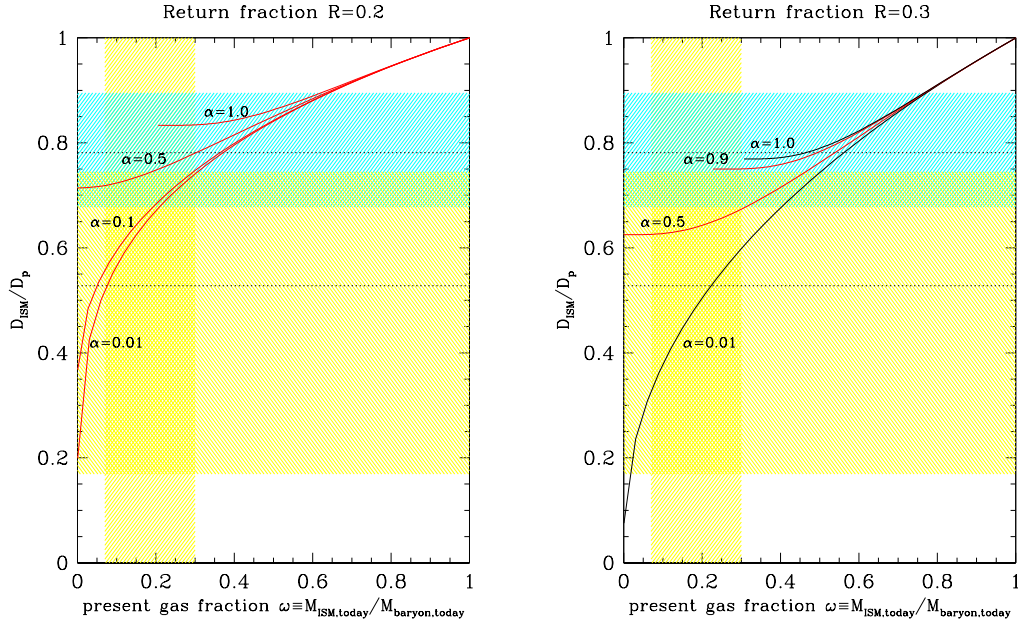
It is also apparent in Figure 1 that as the infall rate  $\alpha$  gets larger the curves that reflect possible solutions begin at higher  $\omega$  e.g. for  $R = 0.3$  (Figure 1 right panel),  $\alpha = 0.9$  curve starts at  $\omega \approx 0.2$  while  $\alpha = 1.0$  curve starts at  $\omega \approx 0.3$ . Thus if one was to plot  $D_{\text{ISM}}/D_p$  as a function of  $\omega$  where  $R$  is set, but do that for a wide and continuous range of infall parameters  $\alpha$  and not just for a few discrete values that we used for the purpose of demonstration, one would find that as the  $\alpha$  increased the curves would move upwards – to higher  $D_{\text{ISM}}/D_p$  values, and to the right – would begin at a higher  $\omega$ . This means that there would be an area in Figure 1 where no solutions could be found. This boundary would be defined by combining all starting (lowest  $\omega$ ) values for all possible infall parameters  $\alpha$ , like an envelope, a limiting curve, above which no solutions can be found, for a given return fraction  $R$ .

Expressing the infall parameter  $\alpha$  from (12) and combining it with (11) we find the limiting curve in the form of

$$D_{\text{min}}/D_p = \frac{1}{1 + R(1 - \omega)/(1 - R)} \quad (20)$$

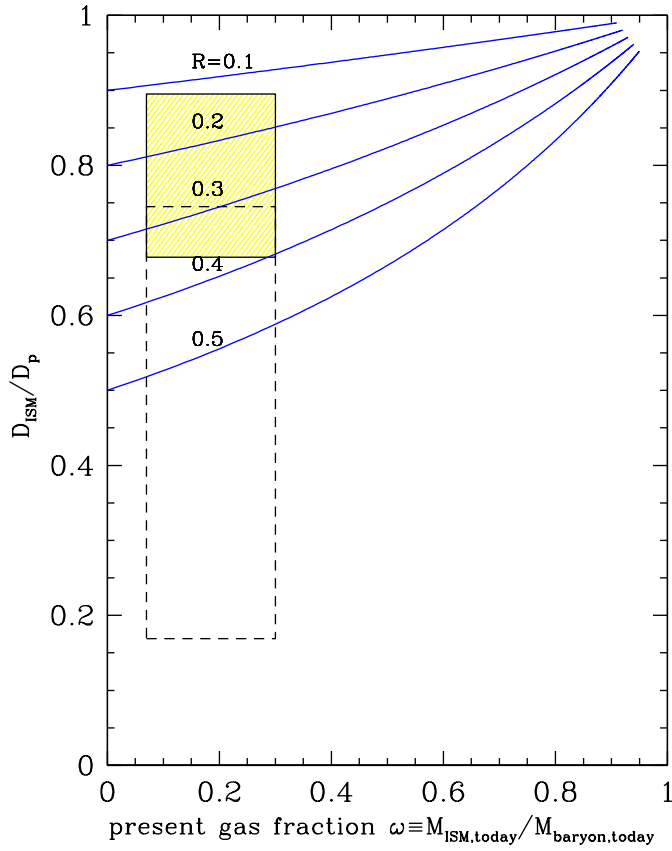
On Figure 2 we plot these enveloping curves for a range of return fractions. The boxes present the overlap region between gas fraction and observed ISM deuterium measurements – yellow box corresponds to dust corrected local deuterium fraction, while dashed box reflects standard local D observations without any dust depletion being assumed [12]. This plot further demonstrates the constraining power of combining deuterium and the gas mass fraction observations – high ( $R > 0.4$ ) return fractions are completely excluded, while low  $0.1 < R \lesssim 0.4$  can allow for a wider range of infall rates.

Figure 3 shows the ratio of deuterium fractions  $D_{\text{ISM}}/D_p$  (top panel) and the gas fraction  $\omega$  (bottom panel) as functions of the ratio of the total present mass to the total initial mass  $\mu_{\text{tot}}$ , which is in the case where no outflow is considered, a measure of the total accreted mass, i.e. the accreted fraction. The curves correspond to three



**Figure 1.** The ratio of the total present-day to primordial deuterium mass fraction  $D_{\text{ISM}}/D_p$  as a function of the present gas mass fraction  $\omega$ . The two panels reflect different assumed return fractions  $R$ . Dot-dashed black line along with the top (cyan) band corresponds to the ratio of the deuterium mass fractions for the ISM deuterium measured by FUSE and corrected for depletion onto dust [12] and primordial deuterium [6] as given in (17). Bottom (yellow) band with the central value of (16) [13] given as a dot-dashed black line corresponds to scatter of deuterium abundances observed along different lines of sight. Vertical (yellow) band reflects the observed range of present gas mass fraction  $\omega_{\text{obs}}$  from (18). Different solid curves correspond to infall rates with proportionality constant:  $\alpha = 0.01, 0.1, 0.5, 1.0$  left panel, and  $\alpha = 0.01, 0.5, 0.9, 1.0$  right panel.

pairs  $(R, \alpha)$  of return fractions and infall proportionalities, while (yellow) bands mark the range of observed values of  $D_{\text{ISM}}/D_p$  and  $\omega$ . These parameter pairs were chosen as representative of models which simultaneously satisfy both observational constraints. It is obvious that gas fraction, as a function of present-to-initial mass (bottom panel), is far more constraining, and that constraints on  $\mu_{\text{tot}}$  for a given set of  $(R, \alpha)$  will also fit within the deuterium observational constraint (top panel). It is clear that  $\mu_{\text{tot}} \gg 1$  in all scenarios, which immediately tell us that accretion is an important factor. From this plot we thus see that the most modest accreted fraction  $2.7 \lesssim \mu_{\text{tot}} \lesssim 5$  is allowed in the case of  $(R = 0.1, \alpha = 0.8)$ , while higher return fractions demand  $\mu_{\text{tot}} \gg 1$ , specifically  $\mu_{\text{tot}} \gtrsim 10$  for  $(R = 0.3, \alpha = 0.9)$ . Since higher return fractions are preferred, this is in agreement with the result that the *most* of the present-day Galaxy was assembled by accretion rather than mergers [47].

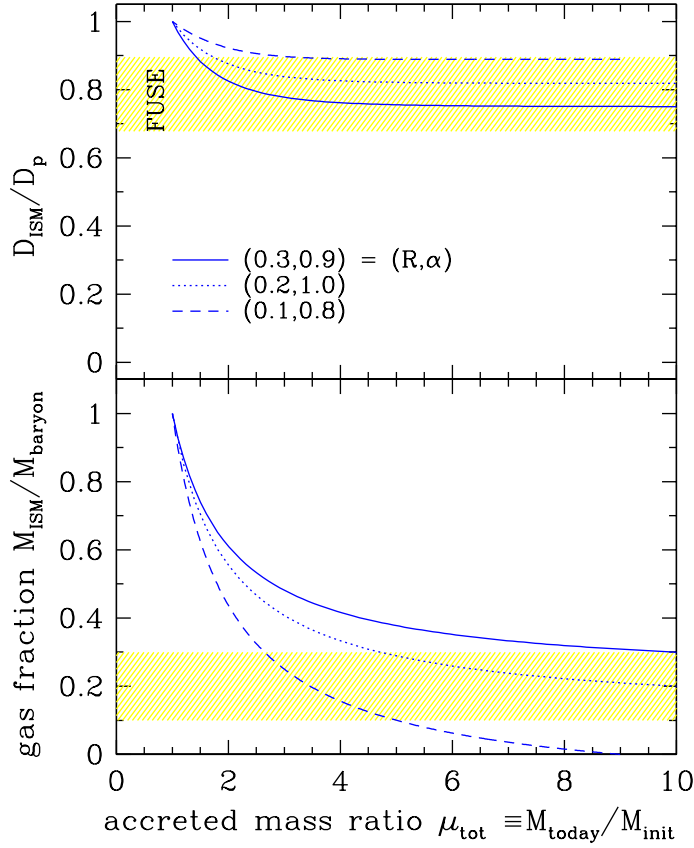


**Figure 2.** The ratio of the *limiting* present-to-primordial deuterium mass fraction  $D_{\text{ISM}}/D_p$  as a function of the *limiting* gas mass fraction  $\omega$ . The boxes present the overlap regions between the observed range the of present gas mass fraction  $\omega_{\text{obs}}$  (18) and measured ISM deuterium abundances with (top, yellow box) and without (bottom, dashed box) depletion onto dust [12]. Different solid curves correspond to return fractions labeled.

### 3. Cosmological Implications of FUSE: D as a Baryometer

Up till now, analysis of high- $z$  D/H observations have assumed that deuterium is not depleted into dust in the unresolved Lyman-limit and damped Ly-alpha systems where it is observed. The FUSE results and their interpretation by Linsky *et al.* [12] at minimum demand that we consider the possibility that this assumption may not be valid.

The possibility of D depletion onto grains would imply that D gas-phase abundances probed in QSOALS represent *lower limit* to the total D/H. This effect goes in the same direction as astration, but astration is expected to be a very small correction in the low-metallicity QSOALS. On the other hand, if D dispersion in QSOALS were present due to depletion onto dust grains, and were as large as suggested by the local Galactic FUSE



**Figure 3.** The ISM-to-primordial deuterium fraction (top panel) and gas fraction  $\omega$  (bottom panel) as functions of the present total-to-initial baryonic mass ratio  $\mu_{\text{tot}}$ . The ratio of the total present mass to the total initial mass is effectively the total accreted mass fraction when no outflow is considered. Yellow bands on both panels represent the observational requirements and thus the results need to be within them. As an illustration, three sets of values for model parameters return fraction  $R$  and infall rate proportionality constant  $\alpha$  have been considered: solid curve  $R = 0.3$ ,  $\alpha = 0.9$ ; dotted curve  $R = 0.2$ ,  $\alpha = 1.0$ ; dashed curve  $R = 0.1$ ,  $\alpha = 0.8$ .

results, the possible upward corrections to the high-redshift D/H could be significant.

As with the local FUSE data, the highest reliable high- $z$  D/H value would be the best estimate of the true D/H value and thus the primordial abundance. One could make this approach more sophisticated by taking a weighted average of several D/H upper limits, in a manner similar to non-parametric approaches which have been used to infer the primordial  $^4\text{He}$  abundance [48]. At the moment, the D data are sparse, and already lower-quality (and lower abundance) results from Lyman limit systems have been excluded from the analysis, effectively performing the upper limit analysis we are suggesting here.

Our other conclusion—that D astration is more or less independent of infall at a fixed metallicity—also has implications for high- $z$  deuterium measurements. Metallicities are available for QSOALS and are small, typically  $Z \sim 1\%Z_{\odot}$ . For any infall model this implies that  $D/D_p \approx 1$  to within  $\sim Z/Z_{\odot} \sim 1\%$  (via A.9). Thus, our results strengthen the case for using high- $z$  observations where metallicity is small. The caveat is that there remain possibilities of outflows, which could be metal-rich and then would not be covered in our analysis.

It is also important to bear in mind that empirically, the low-metallicity QSO absorbers do not show evidence for dramatic depletion of metals onto dust grains [49, 50]. This result stems from the higher ratio of refractory-to-volatile elements in low-metallicity QSOALS relative to the local ISM ratio. The apparent lack of depletion of heavy element onto to grains would in turn suggest that D depletion onto grains may also be small at high redshifts.

All of these issues leave the situation unsettled, but several observational tests suggest themselves. In light of the local FUSE data, additional high- $z$  D measurements become all the more valuable. A larger data set would allow a statistically robust search for a ceiling which would represent the primordial abundance. Also one would look for the kinds of correlations and anticorrelations with metals and temperature that leads to the dust interpretation of the FUSE results. The prescient work of Timmes *et al.* [51] argued that measurements of D ratios with nitrogen and oxygen in QSOALS would be a very useful check on chemical evolution and observationally would eliminate uncertainties due to ionization corrections. In particular, they argue that D/N and D/O can be determined precisely since their atomic properties dictate that these species are locked to hydrogen and thus represent the true abundance ratios. Observation and analysis of the redshift history of D-to-metal ratios in quasar absorbers thus becomes a high priority, not only to determine effects of chemical evolution but also to detect and quantify the extent of depletion onto dust grains.

#### 4. Discussion

Other work has noted a correlation between deuterium and gas fraction evolution which sheds light on our results and the approximations we have adopted. Vangioni-Flam *et al.* [52] made a detailed study of the Galactic evolution of D/H in closed-box models, and emphasized the strong correlation of D/H with gas fraction. Our results confirm this trend for infall models and for general star formation histories. These authors [52] also explored the effect of the instantaneous recycling approximation (IRA) which we have adopted in this work. For some of the models (i.e., for some star-formation histories) they examined, the evolution *with time* of both D/H and gas fraction are not strongly affected by the IRA. Models, in which the time evolution of D/H and gas fraction can be significantly different with and without IRA, were also identified [52]; however, these models lead to unphysically low D/H at late times. Moreover, it was found [52] that the evolution of D/H versus gas fraction—i.e., the co-evolution of the observables—is most

sensitive to the IRA at intermediate times when the fractions lie far above observed values; at gas fraction value close to those observed, the IRA result for D/H comes to within  $\sim 30\%$  of the non-IRA value. The upshot for our work here—which uses the IRA but allows for infall and arbitrary star-formation rates—is that the quantitative constraints on infall are probably good to no better than  $\sim 40\%$  and that the true results *will* depend on the details of the Galactic star formation history. However, our main qualitative point remains unchanged: a high interstellar D today together with a low gas fraction requires large infall.

Although this goes beyond the scope of our simple but instructive model, we will here briefly comment on two major approximations used in our model – infall proportional to the star-formation rate, and the lack of outflow. If the infall rate is decoupled from the star-formation rate, but in such a way that there is a large infall very early on, this extreme scenario would amount to just having a larger initial total mass which would not affect the late-time deuterium history probed by ISM observations today. In a more general framework, one could view our resulting infall rates as the average of the true infall history weighted by the star-formation rate history. Detailed models of deuterium evolution with different infall histories can be found in e.g. [53, 54]. As we have seen from Figure 2 the return fraction  $R \approx 0.4$ , which would result from using currently preferred IMF [40, 41], is just barely allowed. However, if the outflow was included in our model, but in such a way that there is still a positive net inflow of gas, the resulting curves presented on Figure 2 would move upwards on the lower gas fraction side of the plot, allowing for larger return fractions. Looking at the Figure 1, this also means that a given deuterium fraction could now be facilitated with a smaller infall rate, for a given gas fraction, than in the no-outflow scenario. This is easily understood when one recalls that the infalling material is D-rich while the outflowing gas is D-poor, and thus the ISM deuterium is more easily replenished. On the other hand, any outflow must also dilute the ISM of metals, which could result in a demand for unreasonably large stellar metal yields (see Appendix A for further discussion).

The evolution of D has been illustrated in global models of *cosmic* chemical evolution [26], with noticing the resulting dependence on gas fraction. The authors [26] note a connection with local interstellar D/H variations and point out that local deuterium measurements may not be reliable probes of the primordial abundance. Our findings are in agreement with these general conclusions, though if deuterium variations are largely due to dust depletion effects, the difficulties in using local D/H for cosmic probes stem at least as much from uncertainties in estimating the degree of depletion. Moreover, this in turn raises the question of how deuterium dust depletion might affect systems at high redshift.

Finally, we reiterate that our results have been designed to explore the consequences of proposal that interstellar D/H is quite high due to a significant depletion of deuterium onto dust grains [12]. That we are able to find chemical evolution models which can accommodate this result provides a sort of existence proof that workable evolutionary scenarios can be found. But in models which reproduce the high D/H today, the needed

return fractions and metal yields strain at current favored IMF choices, and suggest both a relatively large sequestration of baryons into low-mass stars, but also a relatively large fraction of mass in high-mass stars. More detailed Galactic chemical evolution studies, along the lines of [22] and [21], will be very useful in determining how a holistic picture of Galactic chemical evolution can be understood in light of the FUSE data.

## 5. Conclusions

Linsky *et al.* [12] have used FUSE data to argue that a substantial portion of the deuterium in the the local ISM is not in the gas phase but depleted onto dust grains. This in turn demands upward corrections to the local D abundances, placing the true ISM D abundance at a much higher level than standard GCE models would suggest. In order to explain such high ISM D abundance, a significant infall/accretion of pristine gas appears to be necessary.

In this paper we have shown that another observable highly sensitive to infall is the gas mass fraction, i.e. the ratio of the mass contained in the gas and the total baryonic mass at a given time. Moreover, both the D and gas fraction increase with larger infall (primordial in composition). Within a simple model [31] and by assuming an infall that is proportional to the star-formation rate with proportionality constant  $\alpha$  [33] our results can be summarized in the following

- We find a deuterium mass fraction as a function of the gas mass fraction where the infall rate and the stellar processing return fraction are input parameters. This result is plotted on Figure 1 for a range of infall rates.
- We constrain the allowed infall rates within the observed ranges of deuterium and gas mass fractions that are also plotted on Figure 1.
- Our constraint gets stronger with a higher return fraction. The return fraction of  $R = 0.3$  requires a *significant* infall/star formation scaling that is in the range of  $0.5 \lesssim \alpha \lesssim 1$ .
- We find the allowed range of return fractions to be  $0.1 \lesssim R < 0.4$ ; see Figure 2.
- High return fractions  $R > 0.4$  that are completely excluded or just marginally allowed are preferred by the modern IMF models [40, 41].
- Turning the problem around, recent numerical simulations *predict*  $\alpha \approx 1$  [34], which would *demand* high deuterium today:  $D/D_p \gtrsim 0.77$  for  $R \leq 0.3$ , while higher return fractions are completely excluded.†
- We find a simple universality – ISM D fractions for different infall rates all follow the same trend as a function of metal yields (see the appendix). This is presented on Figure A1. Thus high true ISM abundance can be made consistent with standard GCE models with or without primordial gas infall.

† We thank the anonymous referee for pointing this out.

Our results focus on Galactic chemical evolution, but must ultimately be placed in a larger context of cosmological evolution [24, 25, 26]. Our need for infall is broadly consistent with hierarchical assembly of galaxies by accretion of satellites. Indeed, if just 10% of the  $\sim 10^{11} M_{\odot}$  baryonic mass of the Galaxy is assembled by accretion (as opposed to merging), then the average infall rate over cosmic timescales comes to  $\sim 1 M_{\odot}/\text{yr}$ , i.e., close to the current star formation rate. Moreover, the range of infall parameters  $\alpha \sim 0.5 - 1.0$  in our allowed models are in good quantitative agreement with the cosmic-average results from the gas dynamic simulations [34].

Finally, we note here that the Linsky *et al.* [12] analysis of Galactic deuterium raises a larger question: if the local D is so severely depleted onto dust, should one worry that a similar effect might be at play in high-redshift QSO D observations? Standard BBN theory can only allow for a small upward dust depletion corrections to the high-redshift deuterium abundances before it runs into a problem. Note here however that requiring a higher primordial D abundance would result in a lower primordial  ${}^7\text{Li}$  abundance which could bring resolution to the pressing disagreement between the observed Spite plateau and theoretical predictions of the primordial lithium abundance [5]. High-redshift studies have found that at redshift  $z \sim 2$  dust-to-gas ratio is at the level  $\sim 10\%$  of the one measured in our Galaxy [49]. Thus one should not expect as large dust depletion at high redshifts as has been suggested for the local ISM. Nevertheless, the potential problem that deuterium depletion onto dust could lead to, makes this an important question to ask in the light of the new true ISM D abundance determination [12]. A redshift history of the ratio of deuterium-to-refractory elements like Ti and Si [16, 19], or the deuterium-to-oxygen ratio [51] would be essential for settling the question of the level of D depletion onto dust at high redshifts.

## Acknowledgments

We are grateful to Gary Steigman for insightful comments. We would also like to thank the referee on his comments that helped make this paper better. BDF thanks Shelia Kannappan for enlightening discussions. The work of TP is supported in part by the Provincial Secretariat for Science and Technological Development, and by the Republic of Serbia under project number 141002B.

## Appendix A. Metallicity Evolution

A more accessible but more model-dependent observable of our local chemical evolution is metallicity, whose evolution is normally the focus of GCE models. Although somewhat lower, we will approximate the metallicity of the local ISM with a solar value  $Z \approx Z_{\odot}$  (see eg. [43] and references therein). However, in primordial infall models, stellar enrichment of the ISM is partially diluted by the infall, thus one has to ask what it takes to achieve a solar metallicity ISM.



Taking  $Z$  to be the interstellar metal mass fraction, while  $Z_{\text{ej}}$  is the ejecta metal mass fraction (the metal mass that stars return to the gas) we have

$$\frac{d}{dt}(ZM_{\text{ISM}}) = -Z\psi + Z_{\text{ej}}R\psi \quad (\text{A.1})$$

where we assume the infall of pristine material with no metals. This, now, similar to (8) gives

$$M_{\text{ISM}} \frac{dZ}{M_{\text{ISM}}} = \frac{-Z\alpha + R(Z_{\text{ej}} - Z)}{\alpha + R - 1} \quad (\text{A.2})$$

For the purposes of our analytic treatment, we can approximate metal yields in ejecta in two ways.

(a) *Metallicity-Independent Yields.* We can assume a constant yield:  $Z_{\text{ej}} = Z_{\text{synt}} = \text{const}$ , i.e., *all* stars make new metals with constant yields  $\S$  which are independent of time and of inherited metallicity. Physically, this ignores the recycling of unprocessed initial metals retained in stellar envelopes and returned to the ISM upon stellar death. This is a negligible effect for massive stars which will die as metal-rich supernovae, but can be important for lower-mass AGB stars. Thus this yield approximation can be viewed as an indication of the effect of the lock-up of metals in AGB stars of non-negligible lifetime; in this sense, this yield approximation offers a check on the impact of the instantaneous recycling approximation on metallicity evolution.

(b) *Recycled-Inheritance Yields.* Alternatively, we can account for initial stellar metallicity by writing  $Z_{\text{ej}}(t) = Z(t) + Z_{\text{synt}}$ , where now  $Z_{\text{synt}} = \text{const}$  represents the net *new* metal mass fraction produced by a stellar generation, while  $Z(t)$  is the metal mass fraction that a star was born with. Thus, pre-existing metals from prior generations are returned as well; in the instantaneous recycling approximation we have  $Z(t_{\text{born}}) = Z(t_{\text{end}}) \equiv Z(t)$ . The return of initial metal mass is unimportant for massive stars, which produce far more metals than they are born with. However, the effect is large for lower-mass stars, which represent the majority of the returned mass, and which do not make significant amounts of new metals. In this scenario the yields are manifestly metallicity dependent, in a way that it becomes important when the ISM metal mass fraction  $Z$  approaches  $Z_{\text{synt}}$ ; at  $Z \ll Z_{\text{synt}}$  the difference between the two approximations is negligible.

In the constant-yield approximation (a), by defining new variables  $\Delta(t) \equiv D(t)/D_p$  and  $\zeta(t) \equiv Z(t)/Z_{\text{synt}}$ , we can rewrite (8) and (A.2) as

$$\dot{\Delta}M_{\text{ISM}} = -R\Delta + \alpha(1 - \Delta) \quad (\text{A.3})$$

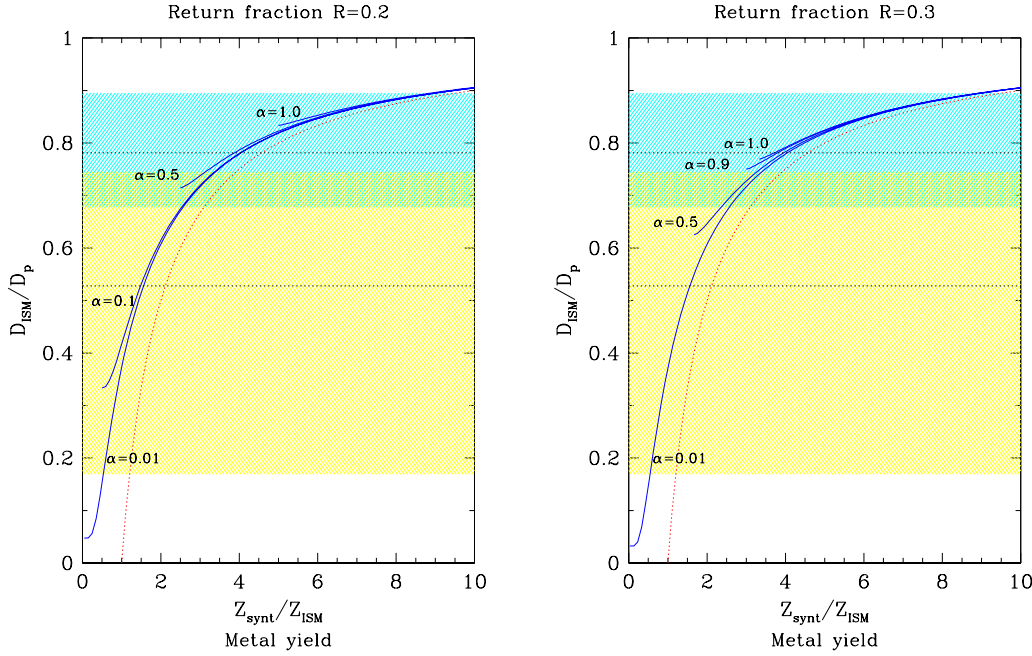
$$\dot{\zeta}M_{\text{ISM}} = -\alpha\zeta + R(1 - \zeta) \quad (\text{A.4})$$

If one makes a further change of variables  $\zeta = 1 - u$ , then we see that  $u$  has an evolution equation identical to that for  $\Delta$  (i.e.,  $u$  and  $\Delta$  both must satisfy A.3). Since  $\Delta$  and  $u$  both have the same initial value  $\Delta(0) = u(0) = 1$ , and satisfy the same equations, then we have  $u = \Delta$  for all  $t$ , which then means  $\zeta = 1 - \Delta$  for all  $t$ .

$\S$  We note here that in our notation,  $Z_{\text{synt}}$  represents a *true yield* of metals rather than the effective yield which is commonly used in the literature [32] and is defined as  $y_Z = Z_{\text{synt}}/(1 - R)$ .

This means that there is a simple connection between deuterium mass fraction and the stellar yield of metals that is independent of infall rate, and is in the form of

$$\frac{D(t)}{D_p} = 1 - \frac{Z(t)}{Z_{\text{synt}}} \quad (\text{A.5})$$



**Figure A1.** The ratio of the total present-day to primordial deuterium mass fraction  $D_{\text{ISM}}/D_p$  as a function of  $Z_{\text{synt}}/Z_{\text{ISM}}$ , i.e., the metal yield at fixed ISM metallicity. The two panels reflect different assumed return fractions  $R$ . The dotted curve (red) reflects an extreme case where only high mass stars are taken into account, i.e.,  $Z_{\text{ej}} = Z_{\text{synt}} = \text{const.}$  Solid curves (blue) reflect a model where  $Z_{\text{ej}}(t) = Z(t) + Z_{\text{synt}}$ , i.e. where both high mass (give constant metal yields  $Z_{\text{synt}}$ ) and low mass stars (return initial metal abundance  $Z(t)$ ) are taken into account. Different solid curves correspond to infall rates with proportionality constant:  $\alpha = 0.01, 0.1, 0.5, 1.0$  left panel, and  $\alpha = 0.01, 0.5, 0.9, 1.0$  right panel. Dot-dashed black line along with the top (cyan) band corresponds to the ratio of the ISM deuterium measured by FUSE and corrected for depletion onto dust and [12] primordial deuterium [6] as given in (17). Bottom (yellow) band with the central value of (16) [13] given as a dot-dashed black line corresponds to scatter of deuterium abundances observed along different lines of sight. [12].

The result of this limiting case is plotted as a dotted (red) curve on Figure A1.||

In the metallicity-dependent yield approximation (b), (A.2) now becomes

$$M_{\text{ISM}} \frac{dZ}{M_{\text{ISM}}} = \frac{-Z\alpha + RZ_{\text{synt}}}{\alpha + R - 1} \quad (\text{A.6})$$

|| Our discussion has focused on the illustrative case in which infall has the form  $f = \alpha\psi$ . However, one can show quite generally that (A.5) holds for arbitrary infall rates within the instantaneous recycling approximation.

which gives the solution in the form

$$\begin{aligned} \frac{1 - R - \alpha}{\alpha} \ln \frac{-Z\alpha + Z_{\text{synt}}R}{Z_{\text{synt}}R} &= \ln \mu \\ Z(t)/Z_{\text{synt}} &= \frac{R}{\alpha} \left( 1 - \mu^{\frac{\alpha}{1-\alpha-R}} \right) \end{aligned} \quad (\text{A.7})$$

At late times,  $\mu^{\frac{\alpha}{1-\alpha-R}} \rightarrow 0$  for all nonzero  $\alpha$ , and we see that in the presence of infall, the ISM metal mass fraction goes to a limiting maximum value

$$Z_{\text{ISM}} \rightarrow Z_{\text{max}} = \frac{R}{\alpha} Z_{\text{synt}} \quad (\text{A.8})$$

We see that infall sets an upper limit to metal mass fraction, and thus the observed ISM metallicity can set limits on infall, given estimates of the mean stellar yield. These limits are comparable to those from D and gas fraction measurements, but are more model-dependent in that they depend not only on the IMF but also on stellar nucleosynthesis yields.

Combining (9) and (A.7) we get a new connection between deuterium mass fraction and metal mass fraction in the form of

$$\frac{D(t)}{D_p} = \frac{\alpha}{\alpha + R} \left[ 1 + \frac{R}{\alpha} \left( 1 - \frac{Z(t)}{Z_{\text{max}}} \right)^{1+R/\alpha} \right] \quad (\text{A.9})$$

We see that deuterium monotonically decreases as the metal fraction grows from zero. As metal fraction  $\rightarrow Z_{\text{max}}$ , we see  $D \rightarrow D_{\text{min}}$ , as expected (11).

Figure A1 illustrates the metal mass fraction evolution for our model (A.9) for a variety of choices of  $\alpha$  ¶. Because our focus is on the present-day ISM, the metallicity is a fairly well-determined value, with metal mass fraction being about  $Z_{\text{ISM}} \approx Z_{\odot}$ . With this fixed, one can view (A.9) as a relationship between deuterium fraction and the stellar *metal yield*  $Z_{\text{synt}}$ , a quantity much less observationally accessible. Consequently, we plot deuterium fractions calculated from the (A.9) as a function of stellar metal yield as solid (blue) curves for different choices of scaling factor  $\alpha$  for the infall rate. We see that, as expected, the higher the infall rate of pristine gas is, the higher the allowed stellar yields have to be. The lower band corresponds to the ratio of deuterium mass fractions  $D_{\text{ISM}}/D_p$  that is not corrected for dust depletion effects, and allows metal yields in the range of  $1 \lesssim Z_{\text{synt}}/Z_{\text{ISM}} \lesssim 4$  for  $R = 0.2$  and  $Z_{\text{synt}}/Z_{\text{ISM}} \lesssim 4$  for  $R = 0.3$ , and infall rates that can at best be as high as the star-formation rate  $\alpha \approx 1$ , but would also be, due to the mentioned universality, indistinguishable. On the other hand, top band plots the high [12] ISM deuterium, which allows for even higher infall rates, and an even wider range of metal yields  $3 \lesssim Z_{\text{synt}}/Z_{\text{ISM}} \lesssim 10$ . This means that yields of metals from high-mass stars have to be at least  $Z_{\text{synt}} \approx 3Z_{\text{ISM}}$  in order for the recent ISM deuterium abundance estimate [12] to be consistent with the present ISM metallicity.

A valid question now is if such mean metal yields are reasonable; this depends on both the IMF and stellar yields themselves. Taking now the supernova metal yield

¶ The curves also fix  $R = 0.2$  (left panel) and  $R = 0.3$  (right panel), but (A.9) shows that the curves only depend on the ratio  $\alpha/R$ , which sets the scaling for other choices of  $R$ .

to be  $Z_{\text{SN}} = 10Z_{\odot}$  [44, 45] we find the total mass averaged metal yield for  $R = 0.3$  to be  $Z_{\text{synt}}/Z_{\text{ISM}} = Z_{\text{SN}}X_{\text{SN}}R_{\text{SN}}/R \approx 4$ . Such yield is not consistent with the upper limit of the D measurements without dust corrections (Figure A1 bottom band), but is consistent with the top deuterium band that corresponds to dust corrections. We also see that a standard simple estimate does, within uncertainties, allow reasonable stellar metal yields as required by the observed range of deuterium abundances.

Moreover, Figure A1 gives reasonable metal yields for the required infall rates presented on Figure 1. Specifically, with a return fraction set to  $R = 0.2$ , a wide range of allowed infall rates  $\alpha$  (Figure 1) allows also for a wide range of metal yields. However, even though this return fraction together with the observed gas fraction would allow infall rate as high as  $\alpha \approx 1.0$  (as shown on Figure 1), the required metal yields would in that case have to be at least  $Z_{\text{synt}}/Z_{\text{ISM}} \gtrsim 5$ , which is difficult to unambiguously rule out but would strain current results for both nucleosynthesis and the IMF. Thus, metal yields in this case provide an additional constraint and tighten the range of allowed infall rates. On the other hand  $R = 0.3$  case and the required infall parameter  $0.5 \lesssim \alpha \lesssim 1.0$ . (Figure 1) allows a reasonable minimal metal yield  $Z_{\text{synt}}/Z_{\text{ISM}} \gtrsim 2$ .

However, Figure A1 also demonstrates that metal yield on its own is not constraining of the infall rate. Though curves for different values of  $\alpha$  terminate at different  $(Z_{\text{max}}, D_{\text{min}})$  values, this is a small effect compared to the fact that they all converge to same values with almost no difference in their shapes. Thus the only way that deuterium-metal connection can constraint different infall rates is by setting the termination point, i.e. by setting the highest infall rate allowed, while all curves for different allowed infall rates would be essentially indistinguishable. This universality with respect to the infall proportionality rate  $\alpha$  demonstrates that the observables  $D$  and  $Z$  are uniquely correlated. However, other observables like gas fraction, as seen earlier, and G-dwarf distribution [46] are indeed sensitive to infall rates and are as such good infall indicators, unlike deuterium abundance, which is an excellent indicator of the nature of metal production, but, as we have shown, is a poor infall indicator.

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